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Analysis

The Energy-emissions Trap

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ABSTRACT

The requirement to reduce emissions to avoid potentially dangerous climate change implies a dilemma for societies heavily dependent on fossil fuels. Reducing emissions will necessitate the transition from relatively high EROI dispatchable fossil fuels to a combination of relatively low EROI intermittent renewables and geographically limited non-intermittent renewables. As renewable capacity requires energy to construct there is an initial fossil fuel cost to creating new renewable capacity. An insufficiently rapid transition to renewables will imply a scenario in which it is impossible to avoid either transgressing emissions ceilings or facing energy shortages; we term this the energy-emissions trap. In this paper, we construct a mathematical model, termed EETRAP, that builds the EROI metric and the energy characteristics of renewable generation into a macroeconomic framework. EETRAP is used for simulation analysis to test how differing assumptions about the EROI of intermittent renewables will affect the time-path of renewable investment necessary to escape the energy-emissions trap. For all runs of the model, the renewable investment rate by 2050 is significantly larger than the current energy investment rate. For declining intermittent renewable EROI, the renewable investment rate crowds out other forms of investment leading to a declining economic growth rate.

1. Introduction

Modern economies heavily dependent on fossil fuels face a dilemma: on the one hand they must transition to renewable energy sources rapidly enough to reduce greenhouse gas emissions so that cumulative emissions remain below the level required for; e.g. a 66% probability of remaining below 2 °C (IPCC, 2015), on the other hand they must obtain sufficient energy supplies while transitioning from high net energy fossil fuels to lower net energy renewables. An insufficiently rapid transition implies a scenario in which it is impossible to avoid either exceeding the 2 °C carbon budget or facing sudden energy shortages; we term this the energy-emissions trap.

Realizing such emissions reductions will necessitate a large-scale investment in renewable energy through the construction of new photovoltaic (PV), wind, and hydroelectric generation capacity (Moriarty and Honnery, 2016; Sgouridis et al., 2016).[1] Other strategies such as the expansion of nuclear power, the use of carbon capture and storage, and the use of bioenergy might also be necessary to facilitate the energy transition. The use of these energy technologies is a source of much debate; most notably between Jacobson et al. (2017) and Clack et al. (2017) concerning the feasibility of transitioning the energy system to one based purely on wind, water and solar energy (WWS) by 2050 (Jacobson et al., 2015). We are principally interested in the scenario outlined in the study by Jacobson et al. and omit analysis of either the feasibility or drawbacks concerning nuclear energy and CCS in the energy transition.

Facilitating the energy transition and escaping the energy-emissions trap will depend critically on the rate at which new renewable capacity is constructed and commensurately, the rate at which emissions decline due to new renewable energy capacity displacing fossil fuels. As noted in the joint study, *Perspectives on the Energy Transition*, produced by the IEA and IRENA, meeting emissions targets would imply an "unparalleled ramp up of all low-carbon technologies in all countries" (OECD and IEA, 2017). The study further notes, however, that in order to achieve the REmap scenario of supplying 65% of total primary energy from renewable sources by 2050, that investment would not need to exceed that currently directed to the energy sector. The purpose of this present study is to examine to what extent the transition to renewables by 2050 will indeed necessitate a redirection of investment to the energy sector above and beyond current levels.

To understand the implications for the energy sector and renewable investment during the transition to renewables requires an understanding of the trajectories of the salient features of an economy (investment, output, emissions, energy demand, economic growth). To this end, we construct a dynamic mathematical model of energy, emissions, and economy termed EETRAP. The construction and simulation of the

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[1] See Sgouridis et al. (2016) for an analysis of the physical quantification of the renewables transition in line with climate constraints.

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EETRAP model is presented in Sections 2 and 3. First, we must deal with energy in some greater detail and explore the key concept of energy return on investment (EROI). Energy return on investment is a measure of the quality of a given energy source calculated as the ratio of the energy delivered by the source to the energy invested in capturing and delivering the energy; it is defined in the following equation (Hall et al., 1979).

$$\text{EROI} = \frac{\text{Energy Returned}}{\text{Energy Invested}}. \tag{1}$$

As the EROI of any given energy source declines towards Eq. (1) unity, it is clear that increasing amounts of energy invested will be required to obtain a given energy return. At unity, EROI represents an energy source that is, using the terminology of Georgescu-Roegen, inaccessible; the energy return matches the energy invested and no remaining energy is made available to perform useful work in society (Georgescu-Roegen, 1976). Indeed, the declining EROIs of certain fossil fuels, through both depletion and the employment of unconventional extraction methods, is sufficiently alarming to cause some researchers to question the feasibility of continued economic growth (Murphy, 2014).

Following a simple calculation, we may derive an expression for net energy available to society. Consider the following definition of net energy:

$$\text{Net Energy} = \text{Energy Returned} - \text{Energy Invested}. \tag{2}$$

Solving Eq. (1) for energy invested and substituting into Eq. (2), we have that

$$\text{Net Energy} = \text{Energy Returned} \cdot \left(1 - \frac{1}{\text{EROI}}\right). \tag{3}$$

We can use Eq. (3) to generate the famous net energy cliff as shown in the following figure.[2]

Fig. 1 displays the nonlinear relationship between the percentage of net energy available for societal use and EROI. As EROI declines from 50 to 10 there is a very gentle decline in net energy available to society; however, as EROI declines further net energy declines very rapidly. The question of whether there is a lower bound to EROI for societal functioning has been raised in previous energetic studies (Hall et al., 2009; Lambert et al., 2014); we address this question briefly in the modelling section of this paper.

Understanding the trajectories for the EROIs of renewable technologies is therefore critical to understanding the energy transition. If renewable technologies have relatively high and non-diminishing EROIs then an energy transition should be at least feasible; however, this may not be the case. The survey of EROI values undertaken in Hall et al. (2014) indicates generally that, excepting hydropower, the EROIs of renewable technologies are at most at par or substantially lower than conventional fossil fuels. Their meta-analysis provides some figures such as the very high mean EROI of 84 for hydroelectric power generation, 18 for wind; 10 for solar (before factoring in grid and storage costs), and generally less than 3 for biomass. For reference, they note an EROI value of approximately 20 for world oil and gas. EROI values for coal are relatively high with a mean EROI of 46 while very energy intensive production processes such as tar sands extraction have much lower EROIs. While the large EROI of hydro might seem to imply an easy route to the energy transition the study notes that the EROI of hydropower is quite variable and that the best locations for the installation of hydroelectric capacity have been developed some time ago; furthermore, there are large environmental costs associated with the construction of such capacity (Hall et al., 1986).

In addition to possessing generally lower EROI values, renewables present two further energetic challenges. First, renewable energy sources, such as wind and solar insolation, can be understood as natural energy flows capturable by a technology such as wind turbines and photovoltaic arrays. Solar and wind energy cannot be harnessed at any rate desired but only at the rate at which is feasible given environmental conditions and the available capacity. Renewables, which require energy investment upfront to construct, provide energy returns only over the lifespan of the technology. Consequently, transitioning from a predominantly fossil fuel based energy system to one based primarily on renewables will require far more energy investment to obtain energy returns of the same magnitude as delivered by fossil fuels. In simple terms, a unit of energy invested in oil might provide 20 units of energy returned if used immediately; this same unit of energy, if invested in photovoltaics, might provide an energy return of 10 but only over time. That the energy return on renewables is not fully available “upfront” but available only over some life-cycle presents a substantial difficulty in the rapid transition to renewables as a large energetic investment must be made initially without a commensurate energy return.

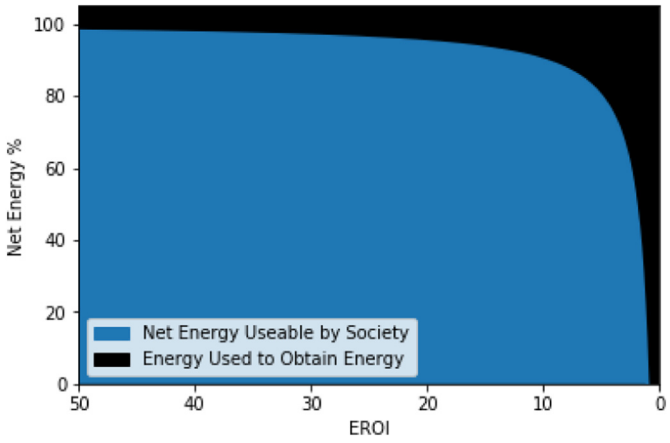

Fig. 1. Net energy cliff.

Secondly, certain renewable energy sources such as solar insolation and wind are subject to intermittency (IEA, 2008). Intermittency limits how effectively renewable sources can approximate non-intermittent energy sources. This problem implies that, without additional electrical storage capacity and sufficient grid flexibility, meeting sudden changes in energy demand with such renewables alone may be infeasible as energy output by intermittent renewables does not necessarily follow energy demand. This intermittency problem is partly solved by the smoothing effect of employing larger numbers of renewable “plants” across large enough spatial areas (Bird et al., 2013), and potentially solved by employing various forms of battery and physical storage (pumped hydro and lithium ion batteries for example). Energy storage however presents its own unique problems. Work, for example, by Barnhart et al. (2013), Carbajales-Dale et al. (2014), and Palmer (2017) indicates that renewables at low market penetration have relatively low storage costs in energetic terms. However, as the penetration increases and displaces conventional dispatchable fuel sources the energetic costs associated with the required grid flexibility and storage may substantially reduce the EROI of the renewables due to energy requirements for both construction and operation of the modified energy system.

Escaping the energy-emissions trap will rely on the rapid construction and deployment of renewable energy technologies characterized by having life-cycle energy returns and the potential of declining EROI due to the energetic costs of mitigating intermittency. To understand the dynamics of this problem, we turn to the mathematical model EETRAP which examines the salient features discussed in this section.

[2] Concept due to Euan Mearns.

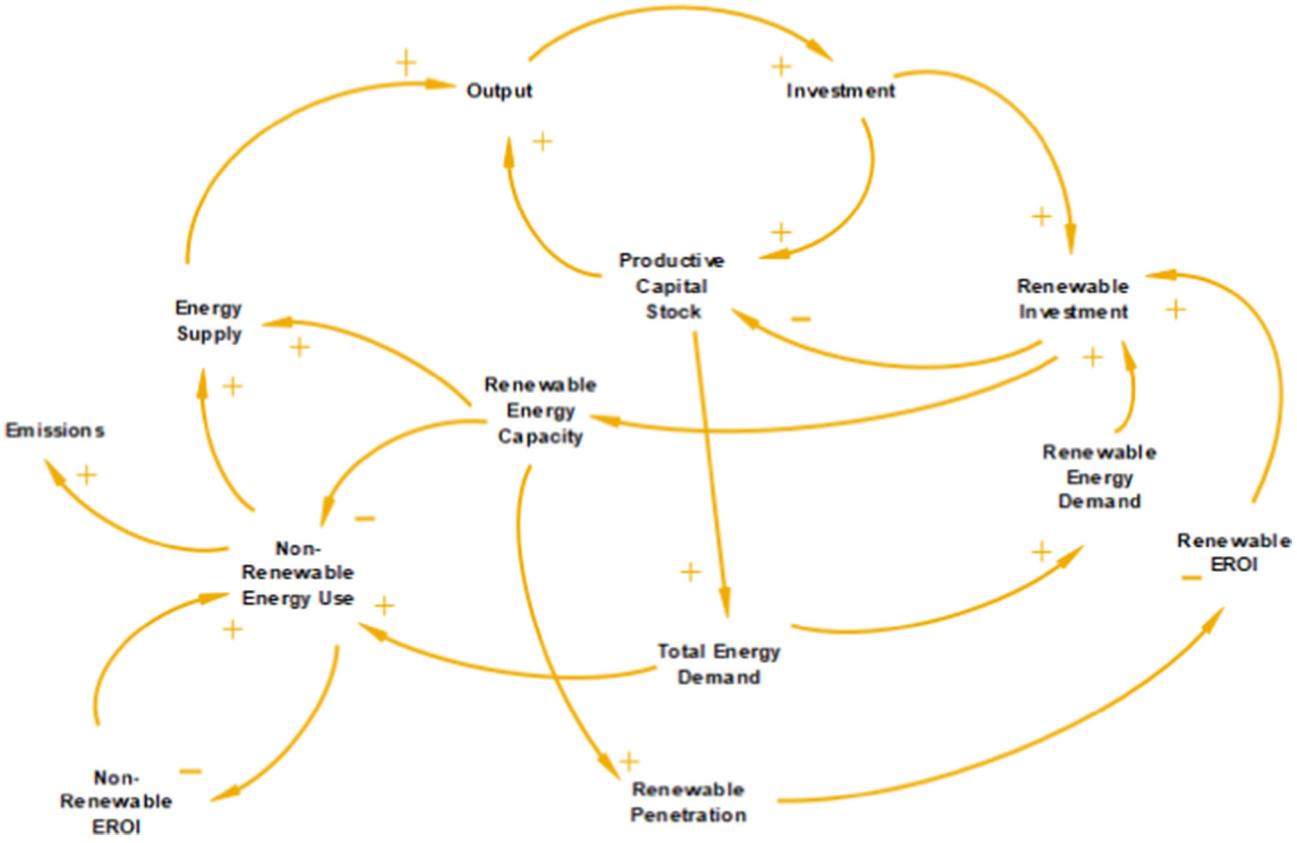

Fig. 2. EETRAP causal loop diagram: main model linkages.

2. The Energy-emissions Trap (EETRAP) Model

The EETRAP model examines the impact of transitioning to lower EROI life-cycle renewables on how an economy allocates its energy use between a primary energy sector and a productive secondary sector. In EETRAP, economic output embodies a certain quantity of energy; this energy can then be consumed or invested[3]. Investment is split between investment the primary energy sector (comprised of a fossil fuel sector and a renewable energy sector) and the secondary sector comprised of non-energy capital stock that is used in production. EETRAP is designed to investigate how these investment rates will change as a result of transitioning to renewables. A high level causal loop diagram of the EETRAP model is shown in Fig. 2.

2.1. Production Function and Inputs

As with conventional macroeconomic models, output (Y_t) in EETRAP is formalized through the use of a production function taking as inputs a productive capital stock K_t and energy E_t; this approach is inspired by the work of D'alessandro et al. (2008). Furthermore, we assume that production is itself driven by demand (in this case by a simple growing exogenous demand). We assume that output Y_t will grow at a given rate as long as the model is not constrained by capital or energy shortages.[4] Letting g_0 denote exogenous demand in period 0 and α_g the growth rate in exogenous demand we have the following expression for g_t:

$$g_t = g_0 \cdot e^{\alpha \cdot t}. \tag{4}$$

Using Eq. (4), we define the production function as follows:

$$Y_t = \begin{cases} g_t & , \min(K_t, \Psi_t E_t) \geq g_t \\ \min(K_t, \Psi_t E_t) & , g_t > \min(K_t, \Psi_t E_t) \end{cases}. \tag{5}$$

By Eq. (5), output Y_t is equal to exogenous demand g_t if the productive capacity of the economy given by $\min(K_t, \Psi_t E_t)$ is greater or equal to the exogenous demand for output; this is shown in the first inequality condition. Alternatively, Y_t equals $\min(K_t, \Psi_t E_t)$ should exogenous demand rise above what can feasibly be produced in the economy given capital and energy constraints. In EETRAP, it is assumed that energy efficiency of production increases over time. These energy efficiency improvements are captured by the monotonically increasing efficiency parameter Ψ_t defined as

$$\Psi_t = \frac{1}{1 - e_{k,t} - e_{r,t}} \tag{6}$$

where $e_{k,t}$ and $e_{r,t}$ and $e_{k,t} + e_{r,t} < 1$ are endogenously determined parameters that model increases in energy efficiency due to the replacement of old capital with more energy efficient new capital and the spillover benefits of renewable investment respectively. Clearly, as Ψ_t increases, any given level of output can be produced with correspondingly less energy input.[5] We employ a Leontief production function to indicate that capital and energy are complements in the production process. Productive capital K_t evolves according to the following difference equation:

$$K_t = K_{t-1} + I_{k,t} \cdot Y_t - \sigma_k \cdot K_t \tag{7}$$

[3] Embodied energy is simply defined as the energy consumed, through extraction and manufacturing for example, in the production of output.

[4] Other inputs such as labour, land, and materials are not included in the production function so that the focus can be on capital and energy. By implication, none of these other inputs are assumed to constrain output growth in the model. For a discussion of the potential role of metals scarcity, see Vidal et al. (2013).

[5] These parameters are defined formally in the appendices. They are endogenously determined and are used to allow for reductions in energy intensity of production while still employing a Leontief functional form.

where $I_{k,t}$ is the capital investment rate and σ_k is the capital depreciation rate. In EETRAP, investment is split between investment in the productive capital stock $I_{k,t}$, renewable energy investment $I_{r,t}$, and fossil fuel sector investment $I_{F,t}$. These investment rates represent a share of a given total investment rate I_T and are related through the simple equation:

$$I_T = I_{k,t} + I_{r,t} + I_{f,t}. \tag{8}$$

Finally, the energy input E_t, which is sum of net energy derived from renewable energy and fossil fuel sources, is written as

$$E_t = E_{f,t} + E_{i,t} + E_{n,t} \tag{9}$$

where $E_{f,t}$ is energy derived from fossil fuels; $E_{i,t}$ is energy derived from intermittent energy sources; and $E_{n,t}$ denotes renewable energy derived from non-intermittent sources. In the following subsections, we will derive the equations that govern both the investment rates and energy variables.

2.2. Fossil Fuel, Fossil Fuel Investment Rate, and CO_2 Emissions

Fossil fuels are modelled as a single depletable stock, denoted N_t, with an endogenously decreasing EROI that declines as the stock is drawn down. The evolution of N_t follows the equation:

$$N_t = N_{t-1} - E_{f,t} - EI_t \tag{10}$$

where EI_t is the energy invested in order to produce the useable energy $E_{f,t}$. Using the ratio of the stock at time t to the initial stock at time 0, we model the fossil fuel EROI, denoted $\text{EROI}_{f,t}$, as follows:

$$\text{EROI}_{f,t} = \text{EROI}_{f,0} \cdot \frac{N_t}{N_0} \tag{11}$$

where $\text{EROI}_{f,0}$, the EROI in the initial time period, is set exogenously. $\text{EROI}_{f,t}$ declines linearly from its initial value as a function of the decline in the size of the stock of fossil fuels. Here, energy invested EI_t follows directly from the definition of EROI; we assume that this energy invested is derived wholly from the stock of fossil fuels itself.

Finally, the fossil fuel sector requires investment $I_{f,t}$ in order to function which is according to two principal factors. First, as $\text{EROI}_{f,t}$ declines an increasing amount of energy and infrastructure is necessary to supply fossil fuels for productive use; secondly, as renewable energy supply increases less fossil fuel energy is necessary to meet energy demand and therefore less investment is necessary to maintain the fossil fuel sector. As such, the fossil fuel investment rate is modelled as follows:

$$I_{f,t} = I_{f,0} \cdot \frac{\text{EROI}_{f,0}}{\text{EROI}_{f,t}} \cdot \frac{E_{f,t}}{\Psi_t \cdot E_t}. \tag{12}$$

$I_{f,t}$ increases as $\text{EROI}_{f,t}$ declines from its initial value $\text{EROI}_{f,0}$ and decreases as the share of the energy input $\Psi_t \cdot E_t$ met by $E_{f,t}$ declines; this share is represented by the third term in Eq. (12). For clarity we note that the fossil fuel sector requires both investment (embodied energy in the form of output) and raw energy input in the form of the fossil fuel stock itself. This is done to model that the fossil fuel sector requires both capital to facilitate extraction and energy to utilize this capital. The use of fossil fuels produces CO_2e emissions which are modelled to be proportional to the magnitude of fossil fuel use.[6] Letting $CO_2e_{T,t}$ and $CO_2e_{y,t}$ define total and yearly emissions respectively, we have the following two equations:

$$CO_2e_{T,t} = CO_2e_{T,t-1} + CO_2e_{y,t} \tag{13}$$

and

$$CO_2e_{y,t} = \xi(E_{f,t} + EI_t) \tag{14}$$

where ξ is a proportionality constant used for calibrating the model.

2.3. Renewable Energy

In order to shift away from fossil fuels, EETRAP constructs two types of renewable energy capacity. The first approximates higher EROI non-intermittent energy generation capacity such as hydroelectric dams; we term this the stock of non-intermittent renewables. The second, termed intermittent renewables, approximates relatively lower EROI intermittent energy generation capacity that is potentially subject to declining EROI as it scales up to replace fossil fuel use.

Both stocks of renewables produce energy in proportion to their magnitude, however, whereas the fossil fuel stock can be depleted to obtain energy at any desired rate (pending sufficient supply) the amount of energy obtainable from renewables is constrained by the amount of existing capacity. Furthermore, though energy is invested up front to create renewable capacity the energy return is spread out over the operational life-cycle of the renewable. We use a difference equation approach to model life-cycle energy production for both renewable types. Letting the stock of intermittent and non-intermittent renewables be termed $R_{i,t}$ and $R_{n,t}$ we examine the energy calculations for intermittent renewables noting that the forms expressed are identical for non-intermittent renewables[7]. The stock of intermittent renewables $R_{i,t}$ evolves according to the following:

$$R_{i,t} = R_{i,t-1} + ([1 - L^{T_{\text{life cycle}}}] \cdot I_{i,t}) \cdot Y_t - \sigma_i \cdot R_{i,t}. \tag{15}$$

The investment rate term, denoted by $I_{i,t}$, is the fraction of the initial renewable energy investment rate $I_{r,t}$ dedicated to each type of renewable with $I_{i,t} + I_{n,t} = I_{r,t}$. Letting $T_{\text{life cycle}}$ represent the operational lifetime of the given renewable technology then the addition of $I_{i,t} \cdot Y_t$ to the stock in time period t is decommissioned and removed from the stock in time period $t + T_{\text{life cycle}}$; this is facilitated using a lag operator L on $I_{i,t}$ that removes additions to the renewable stock made in time period t in time period $t + T_{\text{life cycle}}$. Furthermore, renewables also undergo some depreciation over their life-cycles; for example, solar panels have been found to degrade at a rate of approximately 0.5% per annum (Dirk and Kurtz, 2012). Therefore, in Eq. (15), we see that the stock depreciates at the rate σ_i.

Recalling that output Y_t in EETRAP represents some quantity of embodied energy then $I_{i,t} \cdot Y_t$ also corresponds to a certain quantity of embodied energy; this term can be understood as the energy invested in a given time period t. The energy return associated with this investment is given as a function of the life span $T_{\text{life cycle}}$, the EROI of the given technology, and the depreciation rate. For example, supposing we invest one unit of embodied energy and construct a single unit of renewable intermittent capacity in time t_0 so that $R_{i,t_0} = 1$. By definition, this unit must produce EROI_i energy over its life-cycle. The energy-return for a single unit of capacity, assuming no new investment, is given as follows:

$$\Phi_{i,t} = \phi_i \cdot \left(\frac{EROI_i}{T_{\text{life cycle}}}\right) \cdot R_{i,t} = \phi_i \cdot \left(\frac{EROI_i}{T_{\text{life cycle}}}\right) \cdot R_{i,t_0} \cdot (1 + \sigma_i)^{-(t-t_0)} \tag{16}$$

for $t \in [t_0, t_0 + T_{\text{life cycle}}]$. Here, ϕ_i is a scaling parameter that ensures the following:

$$\phi_i \cdot \int_{t_0}^{T_{\text{life cycle}}} \left[\left(\frac{EROI_i}{T_{\text{life cycle}}}\right) \cdot R_{i,t_0} \cdot (1 + \sigma_i)^{-(t-t_0)}\right] dt = \text{EROI}_i. \tag{17}$$

The condition specified by Eq. (17) is simply that the sum of energy returns from one unit of energy invested over the operational lifetime of a given renewable equates its EROI; an example energy return curve is given in Fig. 3.

[6] EETRAP models total CO_2e equivalent emissions rather than just CO_2e emissions.

[7] The stock of renewables here means the stock of equipment that generates renewable energy. This could be understood, for example, as the number of PV panels installed.

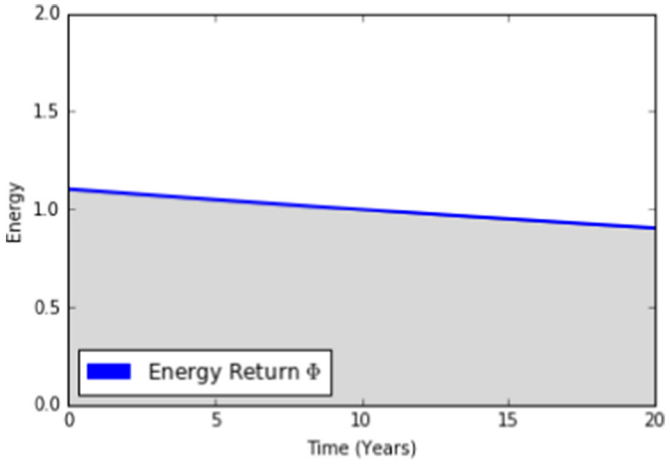

Fig. 3. The energy return curve is shown for a hypothetical renewable with a 20 year life cycle, an EROI of 20, and a depreciation rate of 1%. Using a scaling factor of $\phi_i = 1.103$, the total shaded area under the energy return curve is equal to the EROI of 20.

By Eq. (15), the stock of intermittent renewables grows with new investment and declines with depreciation and units being decommissioned. Older capacity will be more depreciated than newer capacity or simply be decommissioned. While renewable intermittent energy is simply proportional to the magnitude of the renewable stock this stock is made up of capacity at varying stages of degradation. By solving $R_{i,t}$, in Eq. (15), in terms of R_{i,t_0} by repeated substitution, and substituting into Eq. (16) we have that:[8]

$$\Phi_{i,t} = \phi_i \cdot \left(\frac{EROI_i}{T_{\text{life cycle}}} \right) \cdot \left((1+\sigma_i)^{-(t-t_0)} \cdot R_{i,t_0} + \sum_{n=(t_0+1)}^{t} \left[(1+\sigma_i)^{-(t-n+1)} \cdot \left((1 - L^{T_{\text{life cycle}}}) I_{i,n} \right) Y_{i,n} \right] \right). \tag{18}$$

That is, the energy return $\Phi_{i,t}$ reflects the depreciation and life-cycle of each addition to the stock of intermittent renewables. Finally, we note that energy return derived from intermittent renewables $E_{i,t}$ is given simply as:

$$E_{i,t} = \Phi_{i,t}. \tag{19}$$

As such, the energy from intermittent renewables is simply proportional to the stock of renewables, which is subject to depreciation and decommissioning, where the EROI of the technology divided by its operational life span is the proportionality constant. The above derivation is identical for non-intermittent renewables.

2.4. Energy Demand

From the production function in Eq. (5) in Section 2.1, the minimum magnitude of the energy input necessary to produce output with a capital stock of size K_t is determined by the following equality:

$$K_t = \Psi_t E_t$$

which implies that

$$E_t = \Psi_t^{-1} K_t. \tag{20}$$

That is, in order for production not to be constrained by energy at least $\Psi_t^{-1} K_t$ energy must be provided by some mixture of renewables and fossil fuels. Therefore, $\Psi_t^{-1} K_t$ represents the energy demand at time t; we denote this term as ED_t.

In EETRAP, we assume that both intermittent renewables and non-intermittent renewables are necessary to meet energy demand. We make a simplifying assumption that each can meet at most some fraction of total energy demand to avoid the possibility that one renewable type alone can facilitate the transition fully; we denote these fractions as β_i and β_n for intermittent and non-intermittent respectively with $\beta_i + \beta_n = 1$. For clarity, it is assumed that fossil fuels can fully meet energy demand.

By dividing total energy demand ED_t into fractions $\beta_i \cdot ED_t$ and $\beta_n \cdot ED_t$ we can model the demand for fossils fuels for each fraction as follows. Letting $N_{i,t}$ denote the fossil fuel demand to make up energy demand fraction $\beta_i \cdot ED_t$ we have that:

$$N_{i,t} = \begin{cases} \beta_i \cdot ED_t - E_{i,t}, & \beta_i \cdot ED_t > E_{i,t} \\ 0, & \beta_i \cdot ED_t \leq E_{i,t} \end{cases}. \tag{21}$$

The equation for $N_{n,t}$ is identical in form. Eq. (21) simply states that the demand for fossil fuels declines as the energy produced by intermittent renewables $E_{i,t}$ is substituted in for fossil fuels to meet energy demand $\beta_i \cdot ED_t$. Finally, we note that it is the summation of these two fossil fuel demands that comprise $E_{f,t}$ which is given simply as:

$$E_{f,t} = N_{i,t} + N_{n,t}. \tag{22}$$

The extent to which the energy derived from either renewable type meets its energy demand fraction can be used to approximate the market penetration of the renewables in the energy system. Denoting the ratio of intermittent renewable energy $E_{i,t}$ to energy demand $\beta_i \cdot ED_t$ as $c_{i,t}$, we have the following expression:

$$c_{i,t} = \frac{E_{i,t}}{\beta_i \cdot ED_t}. \tag{23}$$

As renewable intermittent energy $E_{i,t}$ grows relative to energy demand $\beta_i \cdot ED_t$ the ratio $c_{i,t}$ increases; we use this ratio to express market penetration.[9]

We can use this market penetration factor to model the decline in intermittent renewable EROI. As noted in Section 2.1, the energetic costs of storage and grid flexibility might rise rapidly as a function of market penetration which would serve to reduce the EROI of the technology. Letting $\text{EROI}_{i,lb}$ denote a theoretical lower bound for $\text{EROI}_{i,t}$ and letting a denote the difference $\text{EROI}_{i,0} - \text{EROI}_{i,lb}$, we have the following:

$$\text{EROI}_{i,t} = \begin{cases} \text{EROI}_{i,0} - c_{p,t} \cdot a & c_{p,t} < 1 \\ \text{EROI}_{i,lb} & c_{p,t} \geq 1. \end{cases} \tag{24}$$

Eq. (24) states that $\text{EROI}_{i,t}$ decreases linearly to some exogenously chosen lower bound as the market penetration of intermittent renewables reaches 100%. For tractability, we model the decline in EROI as a linear process; it is important to note that this is a simplification. At low market penetration, intermittent renewables do not require storage or grid flexibility; however, at higher penetrations these costs may increase non-linearly.

As $\text{EROI}_{i,t}$ declines to its lower bound, the numerator of Eq. (18) declines and as a result net energy produced by the intermittent renewable stock in Eq. (19) falls. As the embodied energy cost of producing intermittent renewables has not changed, this corresponds to a decline in energy return on investment in the model.

2.5. Renewable Investment Rate

The final part of the model concerns how the renewable energy investment rates $I_{i,t}$, and $I_{n,t}$ (and hence $I_{r,t}$) are determined. In EETRAP, a ramp up investment rate $I_{T,t}$ is set exogenously which increases linearly to a chosen value over a given time horizon; $I_{T,t}$ increasing from 0% in 2016 to 2% by 2030 for example. This rate $I_{T,t}$ is split between $I_{i,t}$ and

[8] The derivation of this expression is shown in Appendix B.

[9] The calculation for non-intermittent renewables is identical.

$I_{n,t}$ according to shares λ_i and λ_n respectively. By Eq. (15), we know that the renewable stocks grow due to investment and decline due to decommissioning and depreciation. For renewable capacity to successfully displace fossil fuel use, the renewable investment rate must be sufficiently high so that renewable capacity scales up more rapidly than the growth in energy demand. However, once renewable capacity has grown to meet energy demand this more rapid growth rate, and associated higher investment rate, is unnecessary; at this point the investment rate in renewables need only be such that renewable capacity can meet energy demand. As such, both $I_{i,t}$ and $I_{n,t}$ may be characterized by two distinct regimes; one in which the investment rate ramps up according to the path of $I_{T,t}$ and the other in which the rate is set to ensure the renewable capacity meets energy demand; we term this second regime rate the maintenance investment rate.

To model this maintenance investment rate, it is necessary to know when both the given renewable type successfully replaces fossil fuels and what magnitude of investment is necessary to maintain the renewable stock at a level able to meet energy demand. From Eq. (23), we know that a given renewable has successfully replaced fossil fuels when its market penetration factor is equal to or exceeds one. Using a simple trend extrapolation method, EETRAP forecasts the market penetration factors ahead one year in order to make current period investment decisions; these forecasts are termed $Fc_{i,t}$ and $Fc_{n,t}$ for intermittent and non-intermittent market penetration factors respectively. By Eq. (23), the forecasts of market penetration factors implicitly contain forecasts of the energy demand fractions $\beta_i \cdot ED_t$ and $\beta_n \cdot ED_t$ which are denoted by $FE_{i,t}$ and $FE_{n,t}$ respectively.

In EETRAP, we assume that some excess capacity in the energy system is desirable, therefore renewable capacity in both renewables is constructed until both market penetration factors exceed one by some amount; denote this target market penetration factor as P.[10] Considering non-intermittent renewables, if the forecast of the market penetration factors is less than P then the ramp up investment rate determines the non-intermittent renewable investment rate $I_{n,t}$; if otherwise, then the energy generation capacity of non-intermittent renewables is predicted to meet its energy target and the model changes over to the maintenance investment regime denoted $I_{mn,t}$. This behavioral assumption is displayed in the following equation:

$$I_{n,t} = \begin{cases} \lambda_n \cdot I_{T,t}, & Fc_{n,t} < P \\ I_{mn,t}, & Fc_{n,t} \geq P \end{cases}. \tag{25}$$

The magnitude of the maintenance investment rate $I_{mn,t}$ is determined simply by the percentage difference between the forecasted target future energy demand and current period non-intermittent renewable energy capacity $E_{n,t}$; this implies that EETRAP will invest at a rate necessary to close the gap between current generation and expected target energy demand. $I_{mn,t}$ is given as follows:

$$I_{mn,t} = \begin{cases} 0, & P \cdot FE_{n,t} < E_{n,t} \\ \dfrac{P \cdot FE_{n,t} - E_{n,t}}{P \cdot FE_{n,t}}, & P \cdot FE_{n,t} \geq E_{n,t} \end{cases}. \tag{26}$$

The calculation for the intermittent maintenance investment rate $I_{im,t}$ is identical. Due to the higher and non-declining EROI of non-intermittent renewables it is the case that $E_{n,t}$ will reach a market penetration factor of P ahead of intermittent renewables. At this point, only $I_{mn,t}$ of the $\lambda_n \cdot I_{T,t}$ investment rate will be applied to non-intermittent renewables; therefore, the remaining investment fraction $\lambda_n \cdot I_{T,t} - I_{mn,t}$ is transferred to intermittent renewables. This ensures that the total investment rate at any given time period is being allocated to renewables if the transition has not been completed. This is shown in Eq. (27) which defines the investment rate in intermittent renewables $I_{i,t}$.

[10] In standard runs of EETRAP, $P = 1.1$.

$$I_{i,t} = \begin{cases} \lambda_i \cdot I_{T,t} + (\lambda_n \cdot I_{T,t} - I_{n,t}), & Fc_{i,t} < P \\ I_{im,t}, & Fc_{i,t} \geq P \end{cases}. \tag{27}$$

Finally, we define the renewable investment rate $I_{r,t}$ as:

$$I_{r,t} = I_{i,t} + I_{n,t}. \tag{28}$$

If both intermittent and non-intermittent renewables successfully displace fossil fuels, then the overall renewable investment rate $I_{r,t}$ defines the percentage of economic activity that is allocated to maintain the renewable energy sector.

3. Simulation Model and Scenario Analysis

3.1. Model Initialization and Scenarios

To examine the effects of transitioning to renewables with life-cycle energy returns and potentially declining EROI values, we construct a numerical version of the EETRAP model using the systems dynamics modelling platform Stella. The model is sufficiently flexible that it can be interpreted as both a global representation or a national representation. For the purposes of this study we examine the transition using global parameters. Emissions per year are calibrated such that in the initial period 2016, the model produces 45 Gt CO_2e emissions approximating global emissions in year 2013 (ECCC, 2017). We initialize renewable stocks to provide together 15% of the total energy supply in 2016 in rough accordance with figures for the global energy share of renewables in *Perspectives on the Energy Transition* study. Furthermore, as noted already in Hall et al. (1986) and in USGS (2017), there are geographical limits to the expansion of hydroelectric generation capacity. To reflect this, EETRAP is calibrated by setting the non-intermittent energy demand fraction to $\beta_n = 0.2$ which constrains the stock of non-intermittent renewables from growing much beyond four or five times its initial magnitude. Finally, we initialize the renewable investment rate at 0.6% and the fossil fuel investment rate as 1.8%, the sum of which approximates the share of global GDP made up by energy investment in 2015 (World Bank, 2017). The full list of initialized variables and calibrated parameters is displayed in Table 1.

We examine four scenarios designed to display how the renewable investment rate behaves in relation to different conditions for the EROI values. In order for a scenario to represent a successful energy transition, it is necessary that (1) fossil fuel use be fully phased out in 2050

Table 1
Initialization and calibration table.

Variable name	Symbol	Initial value
Output	Y_0	100
Productive capital	K_0	100
Energy input	E_0	100
Fossil fuel stock	N_0	25,000
Fossil fuel use	$E_{f,0}$	100
Fossil fuel EROI	$EROI_{f,0}$	20
Fossil fuel investment rate	$I_{f,0}$	0.018
Renewable non-intermittent energy stock	$R_{n,0}$	4.05
Renewable intermittent energy stock	$E_{i,0}$	11.9
Renewable investment rate	$I_{r,0}$	0.006

Parameter name	Symbol	Initial value
Exogenous Demand Growth Rate	α	0.03
Productive Capital Depreciation Rate	σ_k	0.03
Emissions Calibration Factor	ξ	0.45
Non-intermittent Energy Demand Fraction	β_n	0.2
Intermittent Energy Demand Fraction	β_i	0.8
Non-intermittent Investment Share	λ_n	0.5
Intermittent Investment Share	λ_i	0.5
Renewable Non-intermittent Life-cycle	$T_{\text{LifeCycle}_n}$	50
Renewable Intermittent Life-cycle	$T_{\text{LifeCycle}_i}$	25

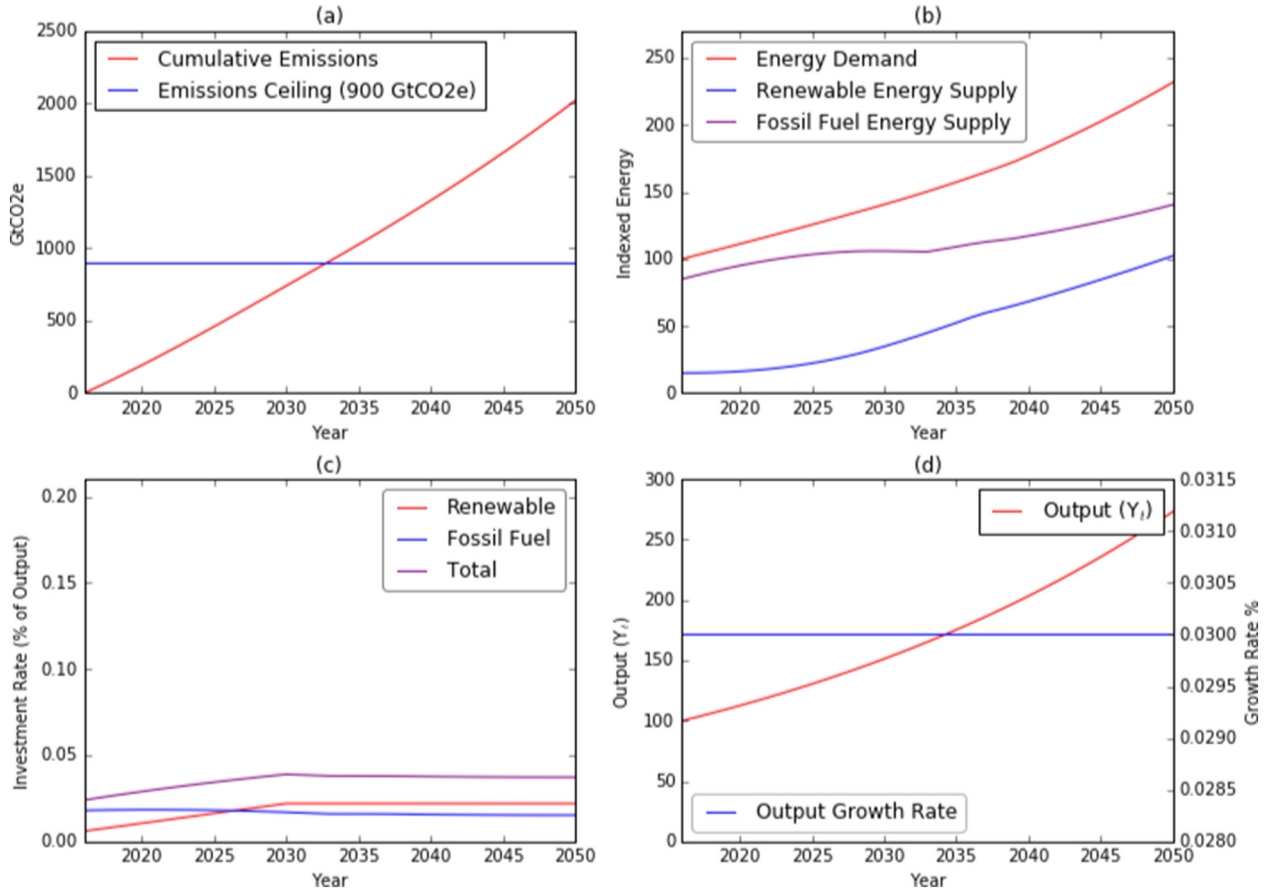

Fig. 4. (a) Cumulative emissions surpass the 900 Gt CO_2e by approximately the year 2033 and continue to rise until the end of the run in 2050. (b) Renewable energy supply (RES), despite its substantial growth from its initial 15% share of total generation, is unable to grow rapidly enough to meet energy demand. After 2040, the growth in renewable energy supply is slower than the growth in energy demand and as such fossil fuel use (NRES) is not phased out. (c) The renewable investment rate increases to 2.2% while the fossil fuel investment rate declines only slightly. The overall energy investment rate increases to approximately 4%. (d) Insufficient resources are shifted away from the productive capital stock to impact the growth in output, as such, output grows at a constant 3% over the run.

and (2) that cumulative emissions do not surpass the 900 Gt CO_2e emissions ceiling.

3.2. Scenario One

For the first scenario, we assume that the EROI of intermittent renewables remains unchanged from the initial value of 15 over the simulation. The renewable investment rate is assumed to rise steadily until 2030 to a value of 2.22% which matches the initial period total energy investment rate. The results are discussed in Fig. 4.

In Fig. 4, we see that economy falls into the energy-emissions trap. By 2030, cumulative emissions have nearly surpassed the emissions ceiling while fossil fuels are still responsible for more than half the energy production in the economy. In this case, as renewables still require some fossil fuel energy to construct, it is essentially impossible for the economy to meet its energy demands and remain below the emissions ceiling.[11] The issue underlying the transition to renewables with life-cycle energy returns is made clear in this scenario. Even with invariant EROI assumptions the energy investment rate necessary to transition to renewables will necessarily be larger than the rate for fossil fuels. Under identical EROI assumptions, we examine how large the rate must become in the following scenario.

3.3. Scenario Two

In scenario two. the renewable investment rate is set so that the economy fully phases out fossil fuels by 2050 while keeping cumulative emissions below the emissions ceiling. The results are detailed in Fig. 5.

In Fig. 5, we see that the renewable investment rate and total energy investment rates rise to over 6% and 7% respectively in order to just meet the energy transition requirements. The implications are simple; the magnitude of the renewable investment rate necessary to escape the energy-emissions trap and to maintain the energy system alone is more than double the energy investment rate prevailing 2016.

3.4. Scenario Three

In scenario three, we assume that the EROI of intermittent renewables declines as a function of market penetration to a lower bound of 8. This scenario models the case where storage and grid flexibility are energetically costly.

In Fig. 6, under the assumption of declining EROI, the energy investment rate must rise to over 10% to facilitate the transition. This large redirection of embodied energy away from the productive capital stock to the energy sector is of sufficient magnitude to disrupt economic growth substantially.

[11] It is mathematically possible to escape the trap at this point. If the renewable investment rate instantaneously increases to 17% then cumulative emissions level off just below the emissions ceiling. However, we rule out the possibility of such sharp increases as they would imply impossibly rapid shifts in the productive makeup of the economy.

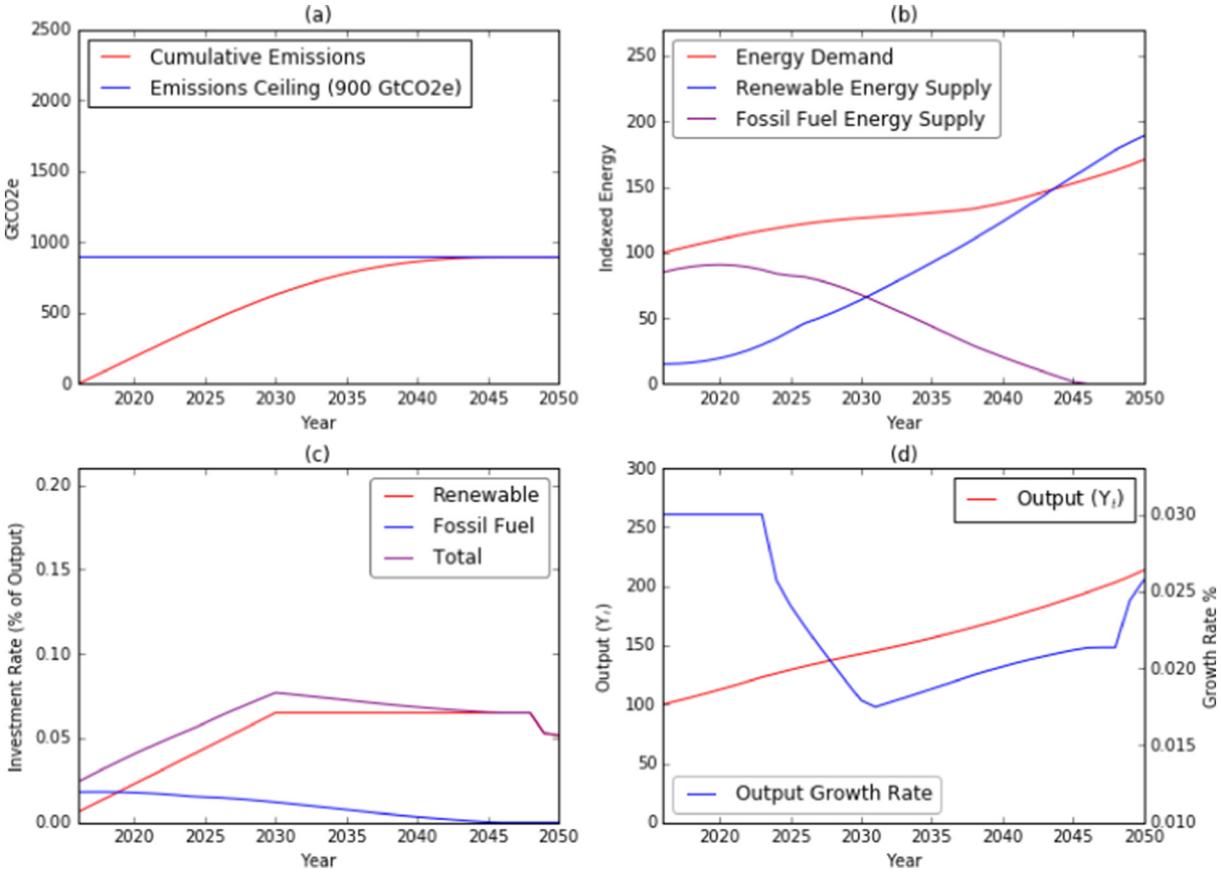

Fig. 5. (a) Cumulative emissions peak at approximately 888 Gt CO_2e by the year 2043. (b) The Renewable energy supply (RES) phases out fossil fuel usage and grows to its predetermined target market penetration factor *P* by 2046. The energy forecasting component of EETRAP maintains renewable energy supply at this target over the remainder of the simulation. (c) The renewable and total energy investment rates increase to over 6% and 7% respectively while the fossil fuel investment rate declines to 0%. The decrease in the renewable investment rate at the end of the run corresponds to the shift of intermittent renewables to the maintenance investment regime. The maintenance investment rate at the end of the run approaches 5%. (d) A sufficient fraction of investment in the economy is directed away from the productive capital stock such that economic growth cannot be sustained continuously at 3%.

3.5. Scenario Four

In scenario three, we see that the decline of intermittent EROI to 8 implies an energy investment rate over 10%, to facilitate the transition. In this scenario, we assume that the EROI of intermittent renewables declines as a function of market penetration to a lower bound of 3 to represent the potentially serious energetic consequences of storage and grid flexibility on EROI; this value approximates that derived by Prieto and Hall (2013). We note that for EROI values lower than 3, the EETRAP model is unable to obtain sufficient net energy through intermittent renewables and cannot fully transition away from fossil fuels.

From Fig. 7, we see that a declining intermittent renewable EROI has dramatic impacts on the evolution of the economy. As the EROI of intermittent renewables declines, the economy must invest up to 17% of its output in renewables alone. This redirection of embodied energy away from the secondary productive capital sector to the energy sector is large enough to collapse economic growth. However, the cumulative emissions, as a result of the slow growth in output, also peak well below the emissions ceiling.

4. Discussion of Results

As we have seen in the previous section, the redirection of investment from the secondary productive sector to the primary energy sector becomes large as the EROI of intermittent renewables declines. Using Eq. (3), we can explore the consequences of this redirection by examining the trajectories for the net energy available to society in each scenario; these are displayed in Fig. 8.

Examining the net energy trajectories for scenarios three and four in Fig. 8, we see a key result of the EETRAP model: the long run consequence of transitioning to renewables with life-cycle energy returns at sufficient pace to avoid transgressing cumulative emissions limits is a decline in the net energy available to society. The magnitude of this decline may be large should the EROI of intermittent renewables decline with increasing share of energy production. Figs. 5, 6, and 7 indicate that the redirection of investment from the secondary productive sector to the primary energy sector leads to a constraint on the productive capacity of the economy and a commensurate decline in output.

While EETRAP indicates the difficulty associated with the energy transition, especially under the scenario of declining energy return on

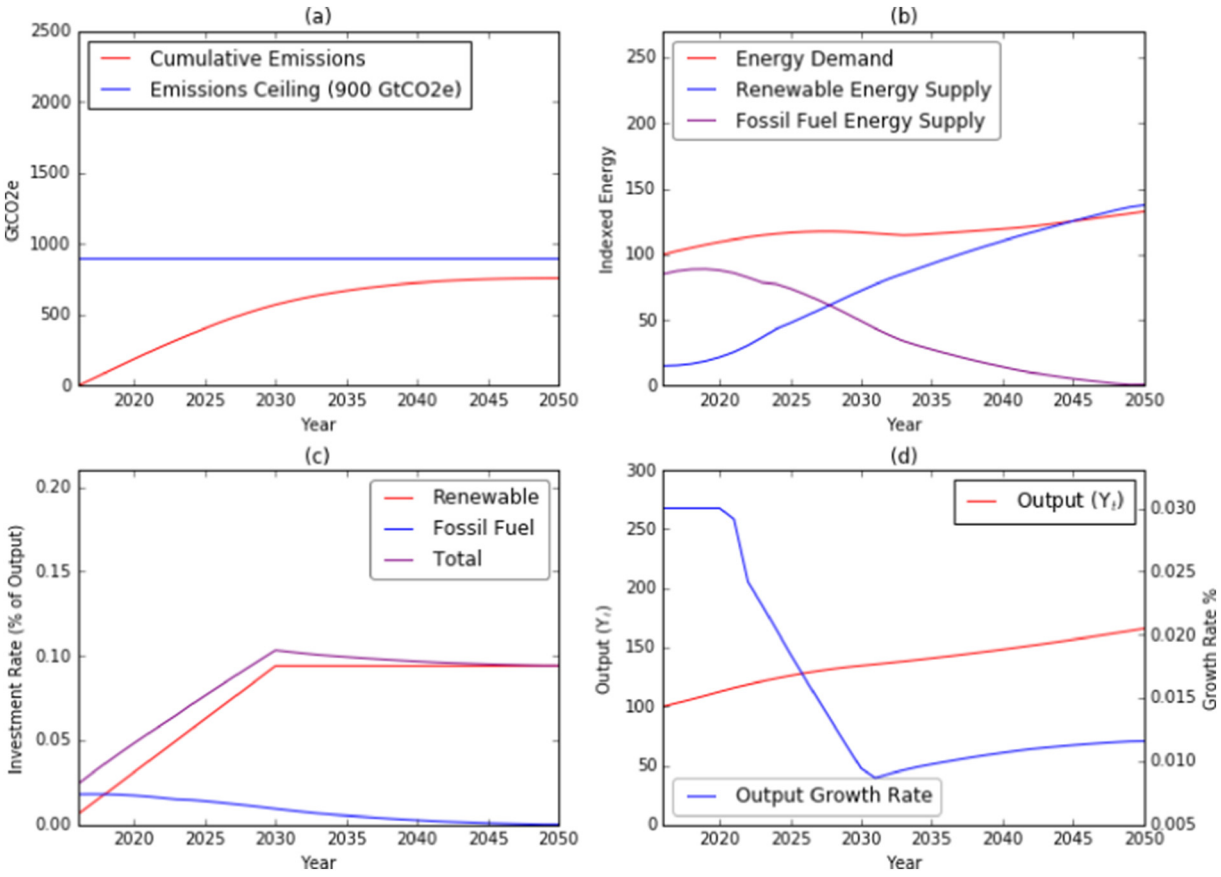

Fig. 6. (a) Cumulative emissions peak at approximately 800 Gt CO_2e by the year 2045. (b) The Renewable energy supply (RES) phases out fossil fuel use but is unable to reach its its predetermined target market penetration factor *P* by 2050. (c) The renewable investment rate and total energy investment rate peak at over 9% and 10% by 2030. (d) A sufficient fraction of investment in the economy is directed away from the productive capital stock such that economic growth cannot be sustained continuously at 3%.

investment, it is necessary to note that many of the model assumptions are still rather optimistic. First, due to the way energy is modelled, the energy payback time for non-intermittent renewables (approximating hydroelectric generation) in the model is less than a year whereas realistically it may be substantially longer (IEA-ETSAP and IRENA, 2015). Secondly, even though EETRAP limits the growth of non-intermittent renewable capacity in the models, EETRAP may construct far more capacity than may actually be feasible. Furthermore, and critically, to ensure model tractability EETRAP does not take into account the construction time necessary to produce intermittent and non-intermittent capacity. As such, EETRAP models a world without construction permits, delays, planning, and political setbacks. Realistically, there is a substantial amount of planning and time necessary to construct and install new renewable capacity which is not reflected in the present modelling work.

Therefore, we note that even under relatively ideal conditions facilitating a successful energy transition in the context of declining intermittent renewable EROI may necessitate a large-scale redirection of society's resources to the energy sector. The results of this modelling experiment indicate that it is still possible to transition to renewables, even in the case of declining EROI, though maintaining steady economic growth in such a scenario may not be feasible. However, as economic growth drives increases in emissions, such continued growth may be neither feasible nor desirable if societies takes seriously the goal of escaping the energy-emissions trap.

Acknowledgments

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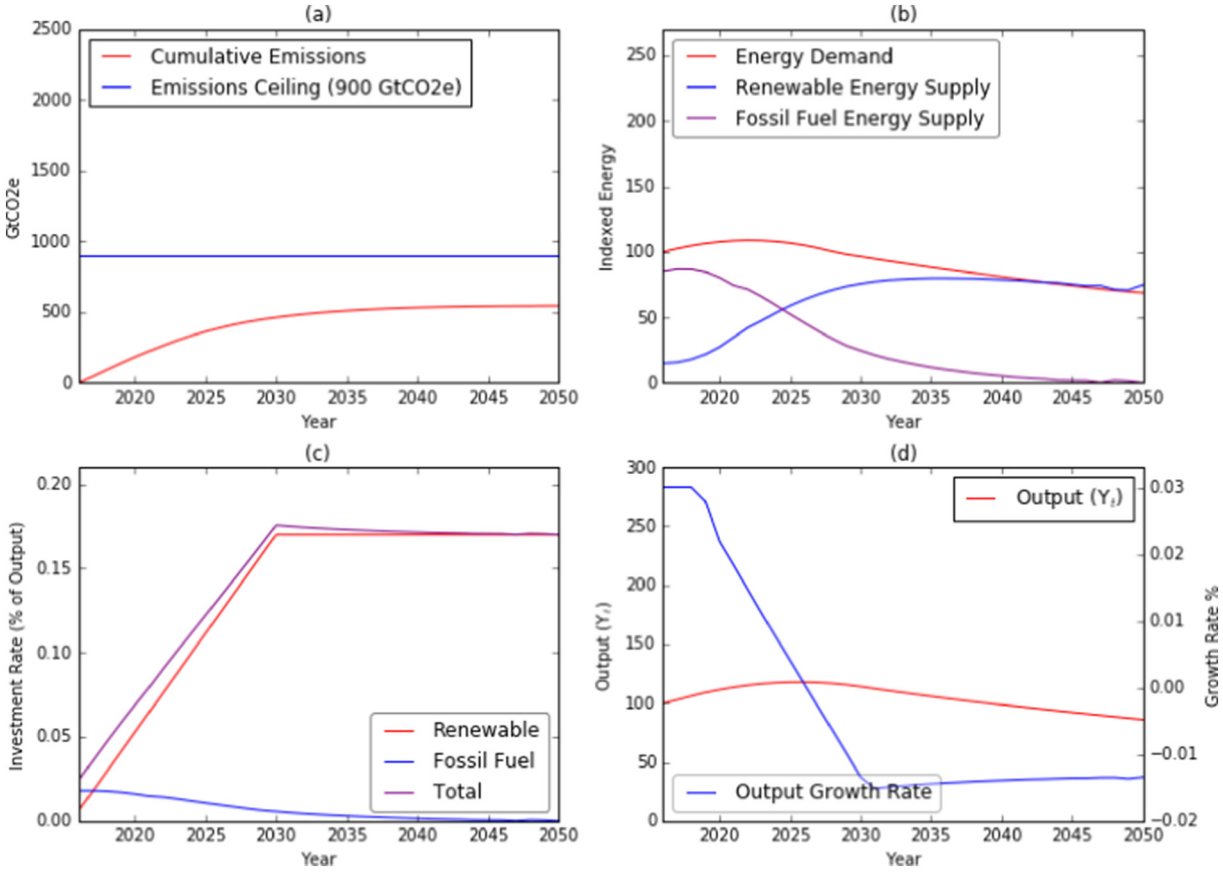

Fig. 7. (a) Cumulative emissions peak well below the emissions ceiling at approximately 550 Gt CO_2e. (b) The Renewable energy supply (RES) just phases out fossil fuel by approximately 2044 but is unable to reach the target market penetration factor. (c) The renewable investment rate peaks and maintains at almost 17%. (d) Economic output increases slowly until about 2025 and afterwards begins a sustained decline. The growth rate collapses to less than −1% by 2030 and remains below this value for the remainder of the simulation.

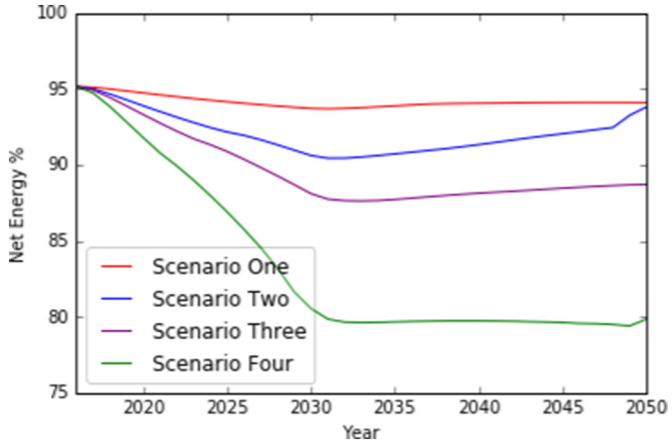

Fig. 8. The ratio of total energy returned (energy available for secondary sector use) to energy invested (energy used by the primary energy sector) in a given year can be used to calculate a yearly EROI value; plugging this into Eq. (3) returns the net energy % available to society in a given year. In all four scenarios, this ratio initially declines due to both declining fossil fuel EROI and the energetic implications of transition to renewables with life-cycle energy returns. In scenario two, the non-declining EROI assumptions permits the ratio to increase once sufficient renewable capacity is installed.

Appendix A

In this appendix, we use the capital sector to define the parameter $e_{k,t}$ from the production function. From Eq. (7), we know that in each time period the capital stock increases by $I_{k,t} \cdot Y_t$ due to investment and decreases by $\sigma_k \cdot K_t$ due to depreciation. Now, let us assume that old capital is replaced by new capital that is more energy efficient and that when the original stock of capital K_0 is fully replaced that energy efficiency increases by γ_1 percent. A simple way to model this is as follows. The original capital stock can be assumed to be fully depreciated and no longer in use when at some time T_{dep}:

$$\sum_{t=0}^{T_{dep}} \sigma_k \cdot K_t = K_0 \tag{29}$$

that is, cumulative depreciation from the beginning of the run equals the magnitude of the original capital stock. Now, we may rewrite Eq. (7) as the sum of all past changes in investment and depreciation up until time T as

$$K_{T_{dep}} = K_0 + \sum_{t=0}^{T_{dep}} I_{k,t} \cdot Y_t - \sum_{t=0}^{T_{dep}} \sigma_k \cdot K_t \tag{30}$$

when the original capital stock is fully depreciated then Eq. (29) holds and therefore we may rewrite Eq. (30) as

$$K_{T_{dep}} = K_0 + \sum_{t=0}^{T_{dep}} I_{k,t} \cdot Y_t - K_0$$

which implies that

$$K_{T_{dep}} = \sum_{t=0}^{T_{dep}} I_{k,t} \cdot Y_t \tag{31}$$

which in turn implies that the existing capital stock at time T_{dep} is comprised only of that capital from new investment and hence represents new capital. It is critical to note that T_{dep} itself is dependent on the rate of investment in the capital stock $I_{k,t}$ and is not constant across different parametrizations. We may rewrite Eq. (31) as

$$\frac{\sum_{t=0}^{T_{dep}} I_{k,t} \cdot Y_t}{K_t} = 1 \tag{32}$$

and note that for $t^* \leq T_{dep}$ that

$$\frac{\sum_{t=0}^{t^*} I_{k,t} \cdot Y_t}{K_t} \leq 1. \tag{33}$$

Now, using Eqs. (32) and (33) as conditionals, we may write the following definition for $e_{k,t}$.

$$e_{k,t} = \begin{cases} \left(\frac{\sum_0^t I_{k,t} \cdot Y_t}{K_t}\right) \cdot \gamma_1 & , \text{if} \quad \frac{\sum_0^t I_{k,t} \cdot Y_t}{K_t} < 1 \\ \gamma_1 & , \text{if} \quad \frac{\sum_0^t I_{k,t} \cdot Y_t}{K_t} = 1 \end{cases}. \tag{34}$$

As the ratio of new capital to the capital stock must range between 0 and 1 then $e_{k,t} \in [0,\gamma_1]$ as desired and increases at the rate by which the old capital stock is replaced by new capital. Now we provide the derivation for $e_{r,t}$. In EETRAP, the spillover effects from renewable investment account for up to 10% energy efficiency improvements. Here, it is modelled through a simple relationship. Assume that energy efficiency due to renewable investment may increase up to γ_2 percent. Then we model $e_{r,t}$ as

$$e_{r,t} = \begin{cases} \left(\sum_0^t I_{R,t}\right) \cdot \gamma_2 & \sum_0^t I_{R,t}) < 1 \\ \gamma_2 & \sum_0^t I_{R,t}) \geq 1 \end{cases}. \tag{35}$$

That is the simple summation of renewable investment rates multiplied by *gamma*$_2$ up until γ_2 is reached. This is a simple but useful way to endogenize efficiency gains to renewable investment.

Appendix B

We can rewrite Eq. (15) as:

$$R_{i,t} = (1 + \sigma_i)^{-1} \cdot R_{i,t-1} + (1 + \sigma_i)^{-1} \cdot ([1 - L^{T_{\text{life cycle}}}] \cdot I_{i,t}) \cdot Y_t). \tag{36}$$

For notational simplicity, we define $(1 + \sigma_i)$ as ω and $([1 - L^{T_{\text{life cycle}}}] \cdot I_{i,t}) \cdot Y_t)$ as π_t. Therefore, we may rewrite Eq. (36) as:

$$R_{i,t} = \omega^{-1} \cdot R_{i,t-1} + \omega^{-1} \pi_t \tag{37}$$

and

$$R_{i,t-1} = \omega^{-1} \cdot R_{i,t-2} + \omega^{-1} \pi_{t-1}. \tag{38}$$

Subbing Eq. (38) into Eq. (37) and rearranging we have

$$R_{i,t} = \omega^{-2} \cdot R_{i,t-2} + \omega^{-2} \pi_{t-1} + \omega^{-1} \pi_t. \tag{39}$$

To write $R_{i,t}$ in terms of R_{i,t_0}, we proceed by repeated substitution as used to produce Eq. (39). That is, we substitute in $R_{i,t-2}$, $R_{i,t-3}$, ..., R_{i,t_0} and rearrange iteratively to obtain the following:

$$R_{i,t} = \omega^{-(t-t_0)} R_{i,t_0} + [\omega^{-(t-t_0)} \pi_{t_0+1} + \cdots + \omega^{-2} \pi_{t-1} + \omega^{-1} \pi_t]. \tag{40}$$

Summing the bracketed sequence, we have that:

$$R_{i,t} = \omega^{-(t-t_0)} R_{i,t_0} + \sum_{n=(t_0+1)}^{t} (\omega^{-(t-n+1)} \cdot \pi_n), \tag{41}$$

Now, substituting back in the full terms for ω and π_t into Eq. (41) to obtain:

$$R_{i,t} = (1+\sigma_i)^{-(t-t_0)} \cdot R_{i,t_0} + \sum_{n=(t_0+1)}^{t} [(1+\sigma_i)^{-(t-n+1)} \cdot ((1 - L^{T_{\text{life cycle}}}) I_{i,n}) Y_{i,n}]. \tag{42}$$

Finally, multiplying Eq. (42) by $\phi_i \cdot \left(\frac{EROI_i}{T_{\text{life cycle}}} \right)$ returns Eq. (18) as desired.

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